Microdynamic issues in large deployable space telescopes

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ABSTRACT

This paper discusses a framework for microdynamic analysis -- analyzing a structure for nonlinear dynamic behavior in the nanometric regime -- and illustrates how microdynamic behaviors such as microlurch, joint snaps, and harmonic distortion fit within the framework. The framework is based on three types of nonlinear load-displacement behaviors associated with hysteresis in joints: deadzone, nonlinear elasticity, and hysteretic damping. The second part of the paper describes microdynamic analyses currently being used to flow optical performance requirements down to stability requirements at the component level. Such analyses are useful during error budget allocation exercises early in the mission design cycle.

Keywords: Precision, optical, deployable, microdynamics, analysis, hysteresis, joint slip, requirements flowdown.

1. INTRODUCTION

Current concepts for deployable space optical systems require nanometric position stability of optical components. One area of great concern is the mechanical stability of the structural interfaces (e.g., joints, hinges, and latches) during flight mission operations under thermal loads, spacecraft slews and other on-board jitter sources. At such low levels of response, a potentially strong source of nonlinearity exists due to friction-induced slippage at the interface contact area. Assessing the structural behavior of interface components, particularly when they exhibit strong nonlinearities, becomes an important factor for accurate optical performance prediction of the instrument.

Work performed in the area of nanometric stability over the last five years has established that microdynamics are a manifestation of <u>nonlinear</u> contact dynamics in the small [1,2]. Deployment and latching mechanisms are a major contributor to microdynamic instability because they typically couple massive components and usually store the largest strain energies in the system. However, all mechanical interfaces, including optics mounts, cables, material matrix and fiber, are capable of microdynamic nonlinearities.

The design of structures to minimize microdynamics is addressed by the microdynamics design guidelines [5]. These guidelines give valuable general principles and strategies for mitigating risks without necessarily requiring a detailed analysis of the structure. Nevertheless, predictive analyses for microdynamics are desirable for a variety of problems. The problem that we are currently faced with, and for which predictive analysis is necessary, is the process of flowing optical performance requirements down to component level structural requirements early in the mission design. To achieve that goal, it is desirable to put microdynamic analyses in a framework or context that can be managed easily.

The objectives of this paper are to: 1) propose an organizational framework for the analysis of microdynamic behavior, and 2) report on the analysis approaches being used to flow optical performance objectives down to mechanical stability requirements on components as part of the error budget allocation progress used in early design stages of the mission.

2. AN ANALYSIS FRAMEWORK

An analysis framework is nothing more than a scheme for arranging and organizing thoughts on microdynamic analysis. Ideally, it captures the essence of the problem--its most basic forms–in a clear, concise, and logical manner. It illuminates patterns, relations between ideas, commonality, and contrasts in the subject matter. Such a framework benefits the users by unifying ideas, providing a consistent interpretation, establishing an image which provides quick understanding and allows for easy communication. Synergism is the ultimate goal -- building on existing ideas to create new ideas, new relations, new insights, new understandings, and better ways of doing things.

The proposed framework is founded on the premise that microdynamics in deployable structures is the manifestation of mechanical hysteresis in the joints. An excellent summary of the relationship between hysteresis and microdynamics, along with recommendations for specific design details, can be found in the microdynamics design guidelines of reference [5]. From a structural response viewpoint, the three essential aspects of hysteresis are 1) that it is an energy dissipating process, 2) that the instantaneous load-deflection relationship is load-path-dependent, and 3) that multiple equilibrium points exist. Because we are dealing with deployable structures where microdynamic structural responses are presumed to be due to hysteresis in the joint (as opposed to material plasticity or viscoelastic effects), we focus only on friction-induced slippage at the mechanical interfaces within the joint.

Lake and Hachkowski [5] have described the total load-deflection behavior of joints as consisting of three types of behaviors (see Figure 1) : deadzones (freeplay), nonlinear elastic effects, and hysteresis damping (cyclic energy loss). These three basic load-deflection behaviors are traceable to physical parameters of the joint and can be measured experimentally. The microdynamic analysis framework is built from these three load-deflection behaviors. The structural behaviors that are hallmarks of microdynamics–microlurch, snapping, and harmonic distortion—are properly placed within this framework in the following discussion.

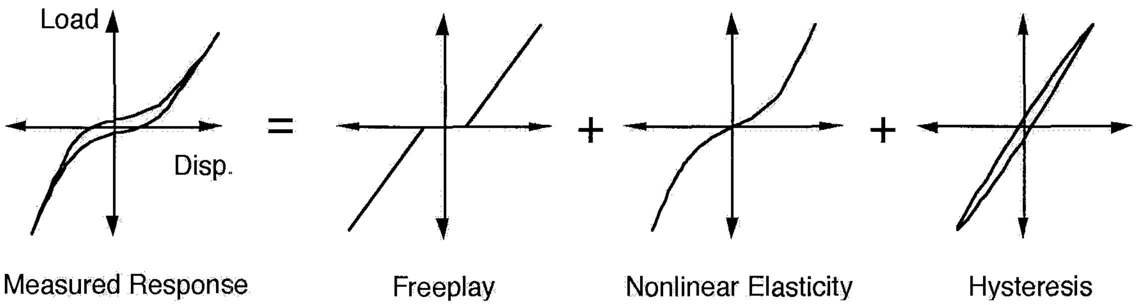


Figure 1 Nonlinear load-displacement behaviors of mechanical joints.

1. Deadzone or Freeplay

Deadzones are related to tolerances or clearances in the interface of the joint. Deadzone may or may not be present in a joint, and it may be partially or entirely removed by the action of preload. Multiple equilibrium points result from joint deadzones since while in the deadzone, the joint can take on an infinite number of configurations. Each of these configurations defines a new structural geometry and potentially new optical alignment. An appropriate analysis may be as simple as a hand calculation of the new geometry, or may entail applying a geometric offset in a finite element model (FEM) and assessing the effect on the alignment through an optical ray trace. This type of analysis is meaningful to missions where the static shape of the structure is more important than deviations from equilibrium due to vibrations.

Impulsive, broadband structural dynamics is excited when the joint configuration suddenly slips from one equilibrium point to another. Also referred to as "joint snapping" this dynamic instability is well documented and is discussed in the second half of this paper.

2. Nonlinear Elasticity

Nonlinearities in the elastic load-deflection response of joints are attributed to different stiffnesses in tension and compression, and to changes in mechanical contact area as a function of loading and unloading. (It may also result from creep in bonded joints, in which case the effects on precision alignment can be evaluated using a succession of static shape analyses as described above.) Creep aside, the primary consequence of nonlinear elastic joints is the harmonic distortion of steady state dynamic forces and the fact that near resonance more than one amplitude can be associated with the steady state response. Harmonic distortion has been measured in the IPEX flight hardware both in ground testing and on-orbit. (Figure 2) The frequency response function of a softening system is shown in Figure 3 and illustrates the neighborhood near resonance that exhibits multiple amplitudes.

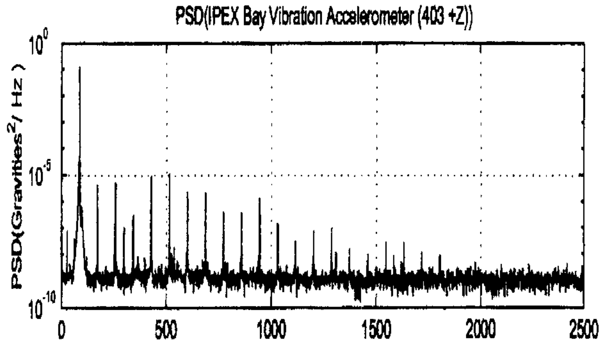


Figure 2 Harmonic distortions measured in the IPEX bay during sine dwell tests [7].

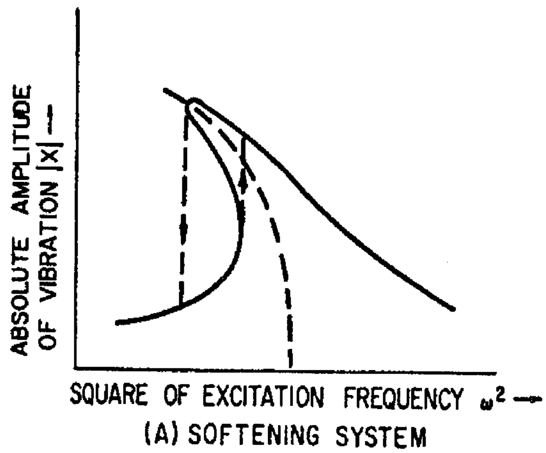


Figure 3 Transfer function of a softening system.

It follows that microdynamics caused by nonlinear elastic joints is of most interest when there is a strong source of steady-state excitation, such as reaction wheels, and where the bandwidth or frequency content of structural response is paramount. One approach to modeling nonlinear stiffness in joints has been investigated using the data obtained during the Cassini spacecraft modal tests, and will be discussed in the second half of the paper.

3. Hysteretic Damping

Cycling a joint through loading and unloading dissipates energy. Damping is not a cause of mechanical instability (unless it is negative), but is a microdynamics issue nonetheless because it relates to accuracy in modeling joint damping in the small strain regime. Certainly friction is one of the primary contributors to energy loss, but accurate models of friction can be complicated, so often an equivalent viscous damping model is used to simplify analysis. Evidence suggests that damping decreases with decreasing strain and decreasing temperature, and as strains enter the microstrain and nanostrain regime, contact mechanics and microslip play a dominant role in determining damping. If damping is too low, the spacecraft may experience excessive settling times after slew maneuvers, excessive levels of jitter, and difficulties for the attitude control system. Simply assigning a very conservative lower bound on damping (such as zero damping) may not be acceptable if that leads to increased costs and complexity of the other subsystems on the spacecraft. More work is needed in this area to derive reliable estimates of damping at the design stage.

Issues of accuracy in modeling damping extend to problems where wave propagation rather than modal response is the appropriate view of the dynamic response. The analysis described in this paper for microdynamic snaps uses simplified linear models, and no allowance is made for localized energy dissipation at joints, or for wave confinement within a component of the structure. This analysis type is documented here for completeness of the microdynamics phenomena, and implementation models have yet to be proposed. However, analysis techniques similar to the ones adopted by the statistical energy analysis (SEA) community might prove fruitful.

It may be of interest to the reader to know that other frameworks were considered before the current deadzone-nonlinear elastic-hysteretic damping scheme was settled on. A scheme whereby a microdynamics failure mode was used for categorization was the leading second choice. Failure modes include peak static displacement due to joint slip, peak transient response to joint slip, peak steady-state harmonic response or response spectra due to nonlinear elastic joint stiffness, and peak settling time due to joint slip. This scheme is attractive because it lends itself to performance requirements that the response falls below the failure mode by some safety factor. A third scheme is to separate analyses by identifying the analysis technique employed and ranking in terms of cost and complexity. The framework proposed here was considered superior because it does a better job of unifying the themes.

3. MISSION REQUIREMENTS FLOWDOWN

Early in the mission project cycle, simplified microdynamic analysis methods will be needed to flow down optical performance objectives to mechanical stability requirements of components. In turn the bounding stability requirements of the components will be used to guide the component design and verification tests. As such, the analysis approaches advocated at the error budget flowdown stage should provide simplified bounding solutions for the more sophisticated component analysis that will be performed once the final configurations, designs, and load paths are known.

This approach to microdynamic modeling is currently being implemented to define the error budget allocation for two NASA ORIGINS space missions: SIM (Space Interferometry Mission) and NGST (Next Generation Space Telescope). Several example microdynamic analyses are presented in the paper. One type of microdynamic analysis models the effects of an impulsive snap. Snap models have been verified using IPEX flight data, and are implemented on SIM for dynamic disturbance assessment. Another type of microdynamic analysis is the nonlinear response to steady-state excitations due to change of interface stiffness during microslip. Nonlinear stiffness models have been validated using the Cassini interplanetary spacecraft modal test data, and will be implemented on SIM to estimate the extent of the response distortion induced by the nonlinearity.

4. MODELS OF JOINT SLIPS

The susceptibility for a joint to slip is a function of the specific joint design, the mechanical load currently being transferred by the joint, and possibly the loading history. Transfer of forces across the interface by tangential friction, a design detail discouraged for precision structures, results in strain energy being stored in the joint, which in turn could potentially be released into the structure. If the strain energy is released slowly enough, there will be no structural dynamics excited, although some static offset and misalignment will be present after the slip. Such a gradual release of energy might be associated with frictional microslip across the surface. A more conservative (and interesting) assumption, suitable for preliminary design and requirements validation, would be that the release of energy is caused by the sudden slip of the interface, a sudden breaking of frictional lock, resulting in dynamic excitation of the entire structure.

The precise mechanics that transpire during a joint slip are complex and not generally amenable to precise modeling. Fortunately, though, if the purpose of the analysis is to bound the dynamic response, the exact kinematics of the joint slip need not be known, as long as it can be shown that the slip used for the analysis leads to a reasonable bound on the structural response. Using as an analog a simple SDOF model subjected to support motion, it can be demonstrated that the bound for structural response is caused by the most rapid change in boundary position; i.e., a step function. Due to the inertia of the moving elements, a ramp function of very short rise time is more appropriate than a step function, but as argued below, this is a fine distinction. Ramp functions are completely described by the rise time, or slip duration, and the amplitude, or slip distance. The amplitude must be dependent on joint design and possibly loading history, and might be determined from joint geometry or perhaps from quasi-static testing of the actual hardware. For rise time, an engineering estimate is that joint slip velocity lies in the range 1 to 1000 micron/sec. However, knowledge of the specific rise time (or slip duration) may not be necessary either. If the slip is less than 1/10th the period of the fastest mode of interest, the resulting structural displacement is largely insensitive to rise time and deviates less than 2% from the maximum displacement due to a step function. That is to say that fast ramps are indistinguishable from step functions. Velocity of structural response is more sensitive to rise time, but like displacement, velocity becomes less sensitive as slip duration decreases.

These observations and the assumptions that they lead to form the basis of a rational method to bound the effects of joint slips, before the structure is built, before the joints are designed, and before the loads acting on the joints are even known. Using these bounding models for joint slips, requirements can be established and validated for the interface components.

A Case Study: The SIM Model

The Space Interferometer Mission (SIM) is a space-based 10-m baseline interferometer under development at Jet Propulsion Laboratory, and targeted for launch in 2006 [8]. As illustrated in Fig 3, the spacecraft consists of four primary systems: Precision Support Structure (PSS or optical bench), external metrology boom, the spacecraft bus, and solar array. At this point in the project evolutionary cycle, the emphasis is on mission requirements definition and preliminary design phases. Using a reference system design, a multidisciplinary (structural, thermal, control, optical) finite element model has been constructed using the Matlab-based program IMOS [9]. This integrated model is capable of predicting structural responses to mechanical and thermal loads, as well as predicting critical optical performance metrics such as interferometer fringe positions and wavefront tilt angles.

To facilitate the rapidly changing design of the various elements of the spacecraft, and to keep the system-level model to a reasonable size, the Craig-Bampton component-mode-synthesis substructuring method was used [10]. In the Craig-Bampton CMS technique, the dynamic response of each component of the system is represented as a set of constraint displacement patterns and a small number of normal modes and generalized coordinates. The components are joined together by kinematic compatibility equations written for the substructure boundary degrees of freedom. The SIM model has sixteen unique components, and in general each component is modeled with just enough of the normal modes to represent the critical response. Fully assembled, the system model has about 1275 normal modes. Historically, the SIM integrated model has been used to generate transfer functions for analysis of reaction wheel disturbances; the use of the integrated model to analyze the system for microdynamic joint slips represents a new area of investigation.

A number of alternatives were considered to implement the joint slip in the finite element method. The selected method must be computational efficient, and of course be consistent with the analysis software and analysis methods available. In itself this can present a significant challenge if working with a general-purpose finite element program. After weighing the alternatives, it was decided to use a double-node at the slip location, and to apply equal-but-opposite external forces at the two distinct nodes, in the direction of the desired joint slip. The forces have a ramp time variation that forces the two nodes apart according to the desired rise time; the magnitude of the forces is determined by the desired slip distance divided by stiffness of the artificial spring spanning the joint in the slip direction. Stiff springs also connect the other five DOFS at the slip joint. Selection of spring stiffnesses can be trick because the added flexibility should not interfere with the structural dynamics, but should not be too stiff that computational costs get excessive. It is absolutely essential to include a deformation pattern that describes the joint slip deformation in the component representation. A normal mode or a Ritz vector work equally well for this. This generalized coordinate must be retained throughout the system analysis to obtain accurate results.

After the system model is synthesized and its normal modes have been determined, the system normal modes are numerically integrated to obtain the transient response due to the joint slip. Economy is realized at this stage by first performing a response spectrum analysis and ranking each mode according to the contribution it makes to each response quantity of interest. Only the modes with significant contribution need be retained in the solution. Depending on the desired output, the

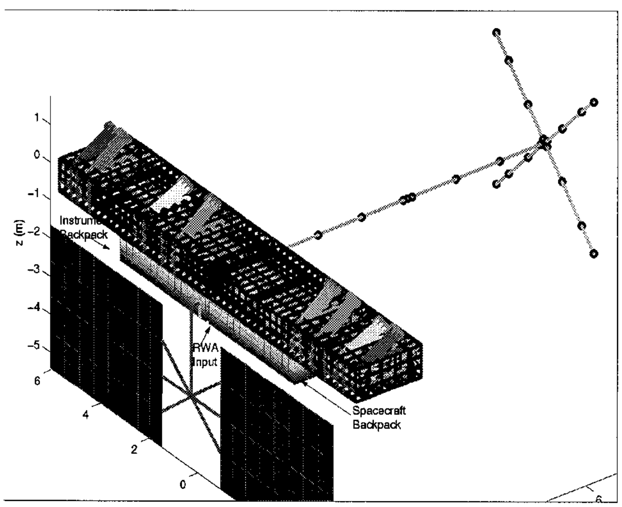


Figure 4. Finite element model of SIM preliminary design. Note the four pairs of telescopes on top of the PSS.

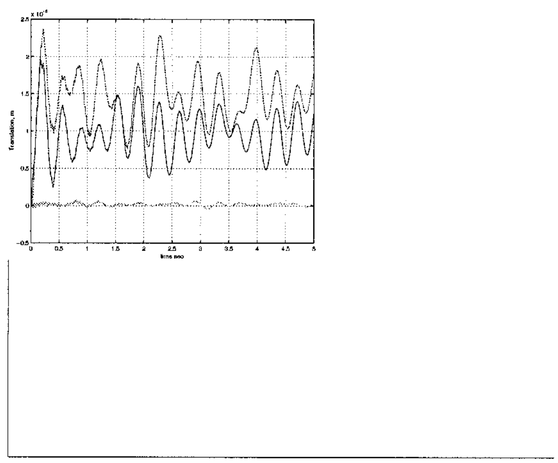


Figure 5 Translational motions in three dimensions of metrology kite vertex due to joint slip at base of metrology boom.

pre-analysis can eliminate between 60% and 90% of the computational expense of the numerical integration compared to integrating all 1275 system modes. In fact, the solution can be terminated entirely after the response spectrum analysis if the predicted responses are far below the allowable levels. Efficient numerical integration of the modal equations is accomplished with an unconditionally stable Newmark method [11].

To illustrate the analysis method, a joint slip has been applied to the base of the metrology boom. This location was chosen because it was thought to be the worst slip location on the spacecraft (although that has not been verified yet) and because in some ways was the easiest location to work with. A rotational slip adjacent to the attachment to the PSS and with a vector direction transverse to the boom longitudinal axis was simulated. The magnitude of the slip was arbitrarily chosen to be 1 micron of displacement with a 0.3m lever arm, or about 3.3 microradians of rotation. A slip duration of 0.01sec was assumed, and 30 seconds of transient response were computed. Shown in Figure 4 is the first five seconds of computed structural motion of an optical reflector (corner cube) located at a vertex of the metrology boom-and-kite structure. As briefly described below, a total of 16 structural and optical performance metrics are of interest to the SIM mission requirements.

For the error budget flowdown process, the joint slip analyses described above are being used in the following manner. SIM science objectives were flowed down to optical quality requirements, which in turn were flowed down to structural motion requirements at key points, particularly at support points for the optics. These requirements include: 1) structural motions of the kite vertices relative to optical elements located on the precision support structure, 2) rate of path length difference for the external metrology laser beams, 3) optical path difference for incoming starlight between interferometer pairs, and 4) wavefront tilt. Some of these requirements relate to maximum instantaneous quantities, while others relate to a root-mean-square value for 30 seconds. The simulated output is then compared to the allowable requirement, and the ratio of allowable to simulated can be used to scale up or down the assumed joint slip magnitude, thus determining the allowable joint slip magnitude. Therefore, there is a distinct and manageable flowdown from mission science requirements down to allowable joint slip magnitudes.

5. MODELS OF NONLINEAR STIFFNESS EFFECTS

As was described previously, joints with nonlinear stiffness properties principally affect response predictions of harmonic loading because of multiple equilibrium points in the regions of the modal frequency, and because of harmonic distortions. This is particularly relevant to space precision platforms, since reaction wheels are the predominant source of steady-state on-orbit disturbance. Furthermore these types of harmonic distortions have been observed both in microslip conditions, as observed in the IPEX data (Fig. 2) as well as in gross slip situations as observed during testing of the Cassini spacecraft [13]. Hence it is believed that predictive models representing stiffness degradation at high load levels should also be valid for low load levels.

Many researchers have proposed models for general hysteretic systems. Some are based solely on mathematical arguments and some are phenomenological models. The model selected for use on the Cassini project is due to Iwan [12]. The model is a distributed system of discrete elasto-plastic elements that is capable of representing an arbitrary degree of stiffness degradation, from gradual to sudden (elastic-perfectly plastic). This type of hysteresis model falls under the broad classification of elasto-plastic systems, which encompasses macroscopic behavior such as gross Coulombic slip in bolted interfaces down to microslip stiffness degradations and non-deteriorating yield of materials.

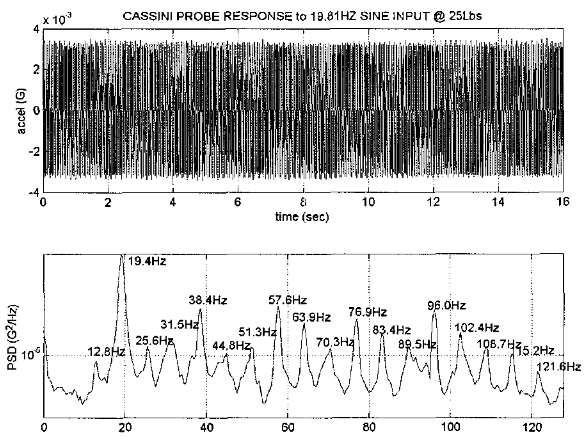
A Case Study: The Cassini Modal Test

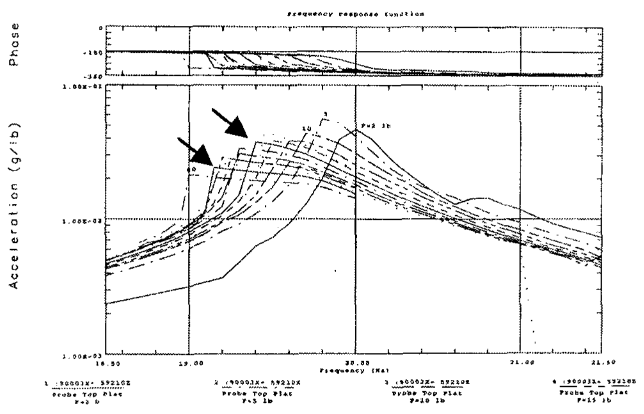
The test data obtained during the Cassini modal tests is used to validate the Iwan modeling approach for elasto-plastic degrading systems. The localized nonlinearity observed during the Cassini spacecraft modal test has been previously reported in [13]. In short, the support joints between the Cassini spacecraft and the Huygens probe mount produced highly nonlinear response during the step-sine tests performed around the primary bounce mode of the component at 19.8Hz. A sample of the step-sine data is shown in Figure 6. The power spectral density (PSD) of the output response shows the characteristic harmonic distortions associated with nonlinear stiffness. The transfer functions, obtained from step-sine tests performed around the bounce frequency for force amplitudes ranging from 9N to 270N, showed severe stiffness degradation as a function of forcing amplitude. (Figure 7). In particular, each data set exhibits a jump in the transfer function estimate as the sine-step frequency moves up across the zone of instability (Figure 3).

A model of the nonlinear stiffness degradation was implemented using the Matlab and Simulink software tools [14]. Using a single degree of freedom representation, the individual microslip stiffness elements of the Iwan model were assigned such that at the lowest force level the effective stiffness of the sum of the individual microslip elements approached the linear modal frequency. Each individual microslip element was associated with a yield level above which it did not contribute to the effective stiffness of the overall system. For the purpose of approach validation, only 11 microslip elements were included in the analysis. More elements are recommended to increase the fidelity of the prediction. Detailed description of the microslip models and parameter identification process will be documented in a future publication.

A Simulink-based recreation of the actual step-sine test process was performed for each step-sine frequency. For each forcing frequency, the amplitude of the transfer function at the frequency of excitation was recorded. It is noted here that since the behavior was nonlinear, harmonic distortion similar to that in the actual test data induced responses at frequencies other than the input frequency [Fig. 6]. The transfer functions were then assembled incrementally for the whole bandwidth of the step-sine test, using as initial condition the last data point from the previous sine frequency response. The analysis was run for both increasing step frequency and decreasing step frequency. Results for the increasing step-sine test simulation using Iwan's distributed elasto-plastic model is shown in Figure 8 for forcing amplitudes of 9N (2 lbf), 110N (25 lbf), 220N (50 lbf). By comparison to the test data in Figure 7, the analytical simulations produced almost identical results, including the location of the jump frequencies. Similar agreements between the data and the analysis were obtained for the decreasing step-sine transfer functions.

This comparison to the Cassini modal test data has shown the capability of Iwan's model to match degrading elasto-plastic systems. These nonlinear models can be incorporated as components into system level models, and then exercised for system level performance assessments. This implementation has yet to be executed on SIM for error budget allocation, however, it is envisioned that stiffness degradation could be parameterized in terms of deviation from linear stiffness over the expected load range.





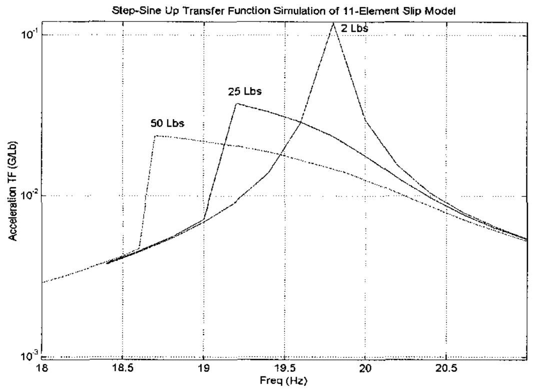


Figure 8 Analytical transfer function obtained using microslip model.

6. CONCLUSION

It is recognized that the system level analyses of microdynamic responses are new, and our understanding of these events is susceptible to change as research continues. The proposed framework represents our current thinking and may have to be modified as more is learned about microdynamics. The bounding analysis for joint snaps is based on engineering judgment and assumptions, and is intended to serve as a reasonable upper bound to the structural responses. But it has not been correlated with experimental measurements. Analyses for nonlinear elastic stiffness in the joints has been initiated, but work remains to be done to understand how to bound the responses by choosing the nonlinear stiffnesses. The whole area of accurate models for joint damping due to microslip needs to be investigated, although it is felt these needs are slightly less pressing at this time.

The current situation for analyzing microdynamics could be contrasted to the 40 or more years of development that have gone into launch loads analysis and testing procedures. Working in the small poses special challenges in itself, whereby standard linear mechanical testing and analyses techniques may no longer be applicable. Furthermore, there has been no "microdynamic failures" to guide us towards the elements of highest risk for the missions. For these reasons, future proposed flight experiments such as NEXUS [15] and MADE [16] will be extremely valuable and will help validate the implementation processes defined herein.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. Hinkle, J.D. and Peterson, L.D., "*An Experimental Investigation of Roughness-Induced Microslip in Metallic Interfaces*" AIAA-99-1382, Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference, St. Louis, Missouri, 12-14 April 1999.

2. Hachkowski, M.R., Peterson, L.D. and Lake, M.S., "*Analytical Model of Nonlinear Hysteresis Mechanisms in a Rolling Element Joint*" AIAA-99-1268, Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference, St. Louis, Missouri, 12-14 April 1999.

3. Gaul, L.and Lenz, J, "*Nonlinear Dynamics Of Structures Assembled By Bolted Joints*", Acta Mechanica, Volume 125, Issue 1-4, 1997, Pages 169-181

4. M. Ingham, and M. Levine, "*IPEX-2 Flight Data Analysis: Quiescent Period Report*", Report JPL D-17912, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, June 1999.

5. Lake, M.S. and Hachkowski, M.R. "*Design of Mechanisms for Deployable, Optical Instruments: Guidelines for Reducing Hysteresis*" NASA TM-2000-210089, March 2000.

6. http://ngst.gsfc.nasa.gov/

7. Hardaway, L.M.R. and Peterson, L.D. "*Stability and Mechanics of Precision Deployable Structures Under Nanometer Deformation*" Doctoral Dissertation, University of Colorado, Boulder, Report No. CU-CAS-00-12, May 2000.

8. http://sim.jpl.nasa.gov/

9. Integrated Modeling of Optical Systems User's Manual, Release 3, 1998, Jet Propulsion Laboratory. (Internal Document)

10. Craig Jr., R.R. and M. Bampton, "*Coupling of Substructures for Dynamic Analysis*," AIAA Journal, Vol. 6, No. 7, July 1968.

11. Newmark, N. "*A Method of Computation for Structural Dynamics*," ASCE Journal of Engineering Mechanics, Vol. 85, No. EM3, July 1959.

12. Iwan, W. D., "*A Distributed Model for Hysteresis and Its Steady-State Dynamic Response*", Proceedings of the ASME Winter Annual Meeting, Paper N0. 66-WA/APM-2, New York, N.Y., Nov. 1966.

13. Smith, K., and C-Y. Peng, "*Modal Test of the Cassini Spacecraft*", Proc. of the 15th International Modal Analysis Conf., Orlando FL., Feb. 1997, Session 21.

14. MATLAB Computer Program, The Mathworks, Inc., Natick, MA. Version 5.

15. Schulthess, M., M. Levine, K. Bell, S. Leonard, and M. Vanik, "*A Joint NASA and DoD Deployable Optics Space Experiment*", Proceedings of the SPIE conference 4013 on UV, Optical and IP Space Telescopes and Instruments, Paper 4013-34, Munich Germany, March 29-31 2000.

16. Peterson, L.D., Lake, M.S. and Hardaway, L.M.R., "*Micron Accuracy Deployment Experiments (MADE): A Space Station Laboratory for Actively Controlled Precision Deployable Structures Technology*" Proceedings of the Space Technology and Applications International Forum, Albuquerque, NM, February, 1999.